Sediment delivery in managed forests: A review

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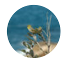

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Abstract: The opening or removal of forest canopies during harvesting or land clearing results in a predictable sequence of responses, the descriptions of which appear remarkably similar around the world. Such activities are now widely acknowledged to have adverse impacts upon water quality and in-stream ecology. Sediment delivery, therefore, encapsulates the dominant process by which water resources are impacted and the process that can be best managed to limit off-site impacts. This paper is a review of current processes, and perceptions, of sediment delivery in managed forests. We outline the major components of sediment and runoff delivery as they relate specifically to timber harvesting activities. Whilst much existing research has focused upon soil loss as the major component of timber harvesting impacts, this review highlights both the need for, and benefits from, a conceptual advance in our thinking of sediment delivery. We advocate that by managing runoff delivery pathways and the resultant pattern of hydrological connectivity, we can limit the potential adverse effects of forest harvesting on in-stream water quality. Specific attention is given here to the interaction of the forest road and track network with both sediment and runoff delivery. The result is a comprehensive account of how best to manage timber harvesting for both on-site sustainability and off-site water resource protection.

Key words: timber harvesting, sediment delivery, road network, connectivity, best management practices (BMPs).

Résumé : L'ouverture ou l'enlèvement de la canopée, au cours des récoltes ou du défrichement, conduisent à une séquence prévisible de réactions, dont la description semble remarquablement comparable partout au monde. On reconnaît maintenant que de telles activités ont des impacts négatifs sur la qualité de l'eau et l'écologie des cours d'eau. Conséquemment, la déposition des sédiments englobe le processus dominant par lequel les ressources en eau sont affectées et le procédé qui peut le mieux être aménagé, pour limiter les impacts au-delà du site. Les auteurs revoient les processus courants, ainsi que les perceptions, de la déposition des sédiments provenant des forêts aménagées. Ils considèrent les composantes majeures des sédiments et la déposition par les eaux de surface, dans leurs relations spécifiques avec les activités d'exploitation forestière. Bien que les recherches conduites jusqu'ici aient mis l'accent sur la perte de sol, comme la composante majeure des impacts de l'exploitation, cette revue souligne à la fois les besoins et les bénéfices qui peuvent générer un progrès conceptuel, dans notre réflexion sur le dépôt des sédiments. Les auteurs proposent qu'en

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aménageant les sentiers de flux des sédiments ainsi que le patron de connectivité hydraulique qui s'en suit, on pourrait limiter les effets négatifs potentiels de la récolte forestière, sur la qualité des cours d'eau. On accorde une attention spéciale à l'interaction des chemins forestiers et du réseau de pistes, avec à la fois le flux et le dépôt des sédiments. Ceci conduit à une perception intégrée permettant de mieux aménager la récolte forestière, à la fois pour la durabilité du site, et la protection des ressources en eau, en aval.

Mots clés : exploitation forestière, dépôt des sédiments, réseau routier, connectivité, pratiques optimales d'aménagement (BMPs).

[Traduit par la Rédaction]

Introduction

Accelerated soil erosion due to forest operations and land-cover change is a critical component of global land degradation. In the developing countries of the tropics, land clearance and timber harvesting are taking place at alarming rates in response to increased demands for agricultural land and hardwood timber (Lal 1990; El-Swaify 1993; Ziegler and Giambelluca 1997*a*, 1997*b*; Douglas 1999). Most of the lowland forests in southeast Asia are now into their second cycle of selective logging with large areas being replaced by plantation agriculture (Douglas et al. 1995; Douglas 1999). The removal of natural hardwood forests is in decline in many developed countries, with increasing areas of forest reserves and National Park. However, there has been an expansion of the softwood plantation industry, renewing concern for the hydrological, geomorphological, and environmental impacts of forest harvesting, removal, and stand conversion.

The opening or removal of forest canopies during harvesting or land clearing results in a predictable sequence of responses, the descriptions of which appear remarkably similar irrespective of geographic location. The environmental impacts of harvesting and land clearing described in recent times for the developing countries of southeast Asia (Douglas et al. 1995) are consistent with past accounts from Europe, the United States, and Australia. This, for the most part, is attributable to the common nature of site disturbances associated with harvesting and land clearing. Activities such as tree removal, fire, and road construction, universally expose large areas of bare ground to the erosional effects of raindrop splash, surface runoff, and wind (Douglas et al. 1995; Ziegler et al. 2000). Some of the more commonly described impacts of these disturbances include increased soil compaction, surface runoff, erosion, landslide risk, and corresponding reductions in soil permeability, fertility, and organic matter. The development of road and track networks as part of logging and plantation agriculture exacerbates problems of surface erosion and runoff development (Megahan 1972; Reid and Dunne 1984; Fahey and Coker 1989; Rijsdijk and Bruijnzeel 1991; Ziegler and Giambelluca 1997*a*; Douglas et al. 1995; Montgomery 1994; Wemple et al. 1996; Luce and Black 1999; Ziegler et al. 2000; La Marche and Lettenmaier 2001) (Fig. 1).

Relative differences in the magnitude of these impacts are often the result of variations in both the intensity of the harvesting and land clearing operation and the prevailing climatic characteristics, notably rainfall intensity. Rates of soil loss from surface erosion processes and resultant sediment discharges, in both pristine and disturbed catchments, are several orders of magnitude higher in areas with high intensity, short duration rainfall events (Douglas 1999). Such intense rainfall events also are characterized by large raindrop sizes, further exacerbating their high erosivity (Douglas 1999). Rainfall intensity, and more specifically the frequency and magnitude of extreme rainfall events, is a dominant control on the nature of runoff generation and hence, on the dominant sediment transport mechanism. The importance of rare and extreme rainfall events in both generating and carrying the bulk of sediment loads, often in the space of a single day, is well supported by the monitoring programs in the humid tropical forest systems of Malaysia (Douglas et al. 1995). Mass movements, although not considered specifically in this review, are well recognised as a significant contributor to sediment generation and delivery in forested catchments with steep terrain and large rainfall events (e.g., Hartman et al. 1996).

Fig. 1. An example of a road network in a forested catchment in the lower Cotter catchment ACT Australia. Note the graveled major road and sidecut midslope access roads used in forestry operations.

These more typical on-site responses of surface erosion, specifically the increased rates of soil loss and reduction in soil nutrient status are now well documented in the literature. Many acknowledge that the understanding required to implement effective soil conservation strategies to manage surface erosion does exist, but the means or desire for strategies is absent (Bruijnzeel 1990). On-site conservation of soil, however, is just one component of land management in forests. The protection of valuable water resources is also a high priority in these environments. Increased sediment loading as a result of accelerated erosion likely affects water quality, aquatic species, and the delivery of nutrients and sorbed chemicals to downstream watercourses (Novotny and Chesters 1989). There is increasing expectation from catchment managers and community groups that scientists can provide practical guidelines to ensure water quality protection in forestry environments.

Our understanding of the linkages between harvesting, forest removal, road construction, and off-site water quality remains tenuous. This, in part, reflects difficulties in accurately measuring the amount of sediment and attached nutrients delivered to, stored and remobilized within, and eventually transported from a river system. Poor understanding of changes in sediment fluxes as runoff moves through the landscape, both on hillslopes and in channels, has resulted in the “sediment delivery problem” (cf. Walling 1983). This gap in our understanding of sediment delivery processes has limited the application and utility of many otherwise sophisticated, physically-based models in predicting catchment sediment yield. It is now clear, however, that if we are to succeed in developing appropriate management strategies in forests, we must strengthen our understanding of the sediment delivery processes and its components.

This paper reviews the major components of sediment delivery as they relate specifically to surface runoff and erosion processes, and hence water quality protection, in managed forests. We present a conceptual framework that emphasises the link between sediment generation due to on-site disturbances and the delivery of this material along specific pathways to the stream channel. Thus this review focuses on the part of the sediment delivery problem between the forest disturbance and the stream. The importance of adopting practices that encourage reductions in runoff and sediment fluxes along these pathways is emphasised using a simple, practical example of the management of road runoff. The review also contributes to an improved understanding of the role and effectiveness of best management practices (BMP) in the control of sediment delivery in forestry environments.

Timber harvesting and water quality

Traditional approaches to the issue

Over the past five decades, the impacts of forest harvesting practices on water quality have been investigated using two common research approaches. The first is a widely reported sediment budgeting approach that quantifies rates of erosion or soil loss from specific landscape elements such as roads, logging tracks, and the general harvesting area (GHA). These data are then often used to construct estimates of pre- and post-logging sediment yield (e.g., Patric et al. 1984; Reid et al. 1981). Estimates of soil loss are traditionally calculated from small experimental plots, simple, empirical relations such as the Universal Soil Loss Equation (USLE) (Dissmeyer and Foster 1980) or combinations thereof. This sediment budget approach, incorporating erosion rates from specific landscape or disturbance areas, together with some arbitrary sediment delivery ratio and scaling component, is widely adopted as a framework for predictive modelling at the larger catchment scale (Haan et al. 1994).

The second approach involves measurements of sediment concentration or turbidity at the outlet of basins of similar geology, aspect, and vegetation. This small catchment approach monitors sediment discharge both before, and after, a period of major disturbance and often uses an adjacent control catchment that remains undisturbed for the monitoring period. Many of the pioneering studies on the impact of land clearing on stream water quality and quantity have been conducted using this approach (Olive and Rieger 1987; Cornish 1989). A review of the literature suggests that, notwithstanding problems of data extrapolation, there is a weak, but general tendency for elevated sediment concentrations or turbidity following periods of logging, roading, and fire (Stott and Mount 2004; Bruijnzeel 2004). However, the data show a high degree of variability in both the magnitude and direction of response (Olive and Rieger 1987; Bren and Turner 1980; Cornish 1989; Doeg and Koehn 1990; Patric et al. 1984; Stott et al. 2001).

Problems with these approaches

Both of these research approaches have inherent assumptions and limitations, many of which are commonly overlooked in our interpretation of the research findings and perhaps more importantly, in the development of effective erosion control strategies. Limitations of the on-site erosion and sediment budget approach are largely associated with defining the sediment delivery ratio necessary to convert on-site erosion estimates to catchment sediment yield (cf. Walling 1983). Quantifying single or fixed delivery ratio remains inherently flawed because of the spatial and temporal variability in some of the controlling factors such as hillslope shape, soil type, vegetation, rainfall intensity, and the degree of disturbance.

A wide variety of landforms and associated sediment sources (gullies, landslides, channel collapse, road sections with surface erosion) are present within a logged catchment. Specification of each of these sources is largely ignored, as in the case of simple, empirical models (e.g., Universal Soil Loss Equation (USLE) or variations thereof) that address only sheet and rill erosion. Alternatively, different processes are invoked to simulate sediment movement from each category of erosional landform (De Roo 1993), thus requiring much site investigation and associated parameterisation.

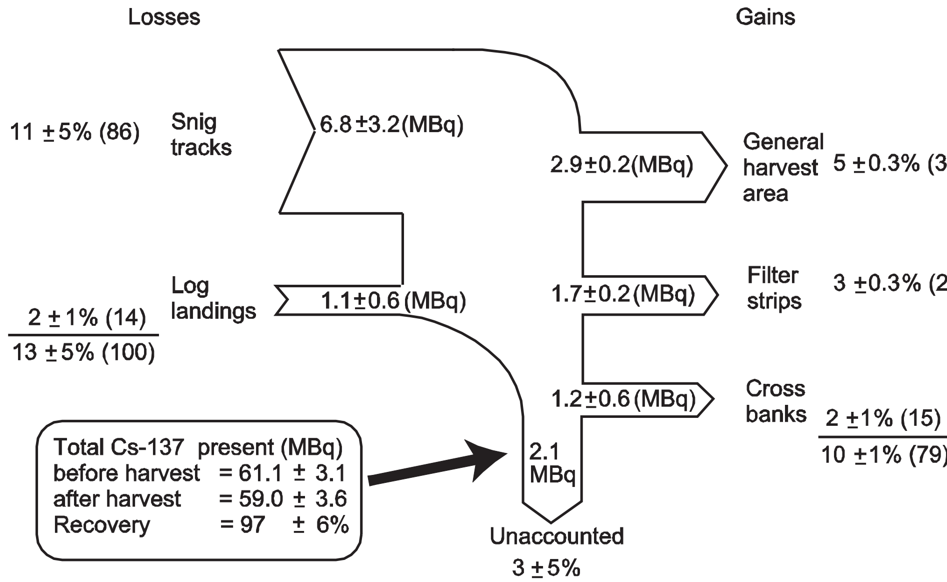
Many catchment sediment budgets and quantitative models also use soil loss data derived from relatively small-scale erosion plots. Not all of the sediment eroded from a particular hillslope is delivered to the stream and there are complex patterns of sediment storage, remobilization, and delivery even within relatively small areas of hillslope (Motha et al. 2003). Even in a disturbed state, trash, litter, stones, and fallen logs remain on the ground surface providing a protective cover for the removal of soil particles from the exposed soil and their delivery downslope. Large volumes of sediment are often produced in small definable areas that may or may not be well represented in the plot-scale data (Bonell and Williams 1986; Croke et al. 1999*b*). Many plots are too small to allow rill and gully formation and also to measure redistribution and storage process within the plot (Croke et al. 1999*b*). Walling (1983) concludes, therefore, that because only a fraction of the sediment eroded from the landscape actually leaves a basin during the course of a monitoring study, estimates of on-site erosion alone are insufficient for developing management programs concerned with off-site practices.

The catchment monitoring approach is commonly referred to as a “black-box” (Walling 1983) where sediment discharge data at the outlet is interpreted without any specific understanding of the source or provenance of material from within the catchment. Elevated sediment fluxes at the catchment outlet are commonly used to infer some process link among harvesting activities, associated soil disturbance, and increased rates of sediment delivery to the stream network. However, material measured at the outlet of a basin is not differentiated according to relative sources within the catchment. In the majority of studies, it remains impossible to link the generation and delivery of this sediment to on-site disturbances due to timber removal, roading or other forms of disturbance. Elevated fluxes at a catchment outlet may be the result of primary site disturbances on the hillslopes, or the remobilization of secondary sediment sources and (or) stored in-channel deposits. Monitoring studies in undisturbed forest systems in southeast Asia, for example, have identified the significance of sediment sources within, and close to the channels, during periods of high sediment output (Douglas et al. 1995). These sources include channel bank erosion, minor landslips, slumping around stream head hollows and outflows from soil pipe systems. In this instance, bank erosion alone is believed to account for at least 50% of the sediment supply to these forest streams. The proportion of the various sources is likely to vary widely between environments. However the potential of each source should be considered for each site.

Estimates of sediment discharge at the outlet are best viewed as a lumped average of all possible sources of sediment within the catchment and some arbitrarily defined estimate of sediment delivery or catchment conveyance. The lumped character of the sediment delivery ratio does not differentiate whether the source of sediment is natural or anthropogenic (man induced). The problems of “spatial lumping” are further complicated in areas where only a fraction of the basin contributes surface runoff, and hence sediment (Walling 1983). These areas are called “hydrologically active areas” and their extent depends on the magnitude of rainfall and rainfall losses and antecedent moisture (O’Loughlin 1981). This extreme spatial variability in sediment generation is, in part, related to the large natural variability in soil erodibility and topographic characteristics of forests (Chappell et al. 1999), but is also related to the localized disturbances produced as a result of selective timber harvesting (Putz 1994). Most simulation models are unsuitable for determining the spatial extent of hydrologically active areas and hence the location of sediment sources. For example, a number of studies have outlined the significance of forest roads as sources of surface runoff and sediment to streams (Reid and Dunne 1984; Ziegler and Giambelluca 1997*a*; Jones and Grant 1996; La Marche and Lettenmaier 2001; Ziegler et al. 2000). Few models explicitly describe roads and their hydrologic influence. Road surfaces may occupy less than 1% of the catchment area but contribute a disproportionate amount of water and sediment during low to moderate rainfall events (Ziegler and Giambelluca 1997*a*; Chappell et al. 1999; Ziegler et al. 2004).

Further limitations of the catchment monitoring approach are introduced in relation to the time-frame for long-term monitoring studies relative to that of catchment response. Elevated levels of stream sediment and woody debris have been measured some 20 to 50 years after logging (Beschta 1978; Webster et al. 1987; Andrus et al. 1988; Platts et al. 1989). Lai (1992, 1993) suggests, for example, that recovery of erosion conditions due to logging in the steeplands of Malaysia may take between 8 to 20 years. This typically extends beyond the time-frame of many monitoring studies. Some long-term

Fig. 2. Tracer-based sediment budget showing the partitioning of soil material eroded (losses) and redeposited (gains) on a forest hillslope in southeastern Australia. Of the total input of Caesium 137 about 13% was redistributed. Tracer levels retained within each element are shown as MBq (a unit of the activity of the radioactive tracer present) within the respective arrow (adapted from Wallbrink et al. 1999).



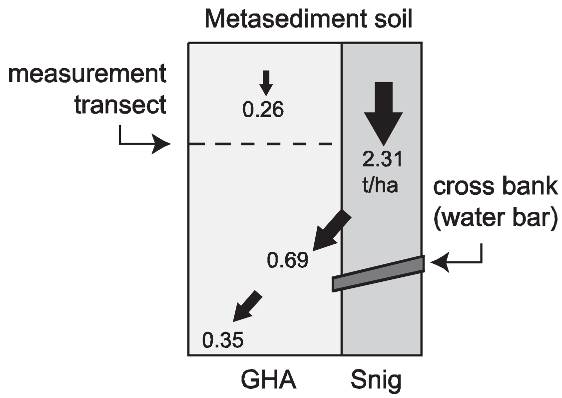
catchment monitoring sites in the United States contain records longer than 30 years (e.g., Hubbard Brook experiment described in Likens 2001). There is only one Australian experimental catchment (MMBW, Coranderrk Experiments) that has been studied for more than 30 years with the majority investigated for periods of less than 15 years (Doeg and Koehn 1990). The importance of long-term monitoring studies to truly appreciating the nature of catchment response to harvesting and land clearing, particularly under extremely variable rainfall conditions, has been outlined in a number of reviews (e.g., Douglas et al. 1995).

There is also the secondary problem of the accuracy of the suspended sediment data due to difficulties of matching the rainfall record in the pre- and post-disturbance measurement periods, storm event sampling, and technical equipment failures. The practicalities of sampling during periods of extreme rainfall events often means that these data are absent from many monitoring records. Cyclones in many parts of south east Asia may occur on average twice a year but sediment sampling is often impossible due to flooding of access routes and the destruction of automatic sediment samplers (White 1990; Douglas 1999; Douglas et al. 1999). Poor sampling frequency means that suspended sediment peaks and total loads have probably been underestimated, bed-load levels and deposited sediments have largely been ignored (Doeg and Koehn 1990). Overall, short-term catchment monitoring studies are of limited value in understanding the magnitude of the sediment transport or in pinpointing best options for remedial or preventative practices within the catchment.

Recent advances in techniques and application

There have been recent advances in both research approaches. Catchment studies have benefited considerably from the introduction of conservative sediment tracers to “finger print” the sources of sediment within a catchment (Ritchie et al. 1974; Walling et al. 1986; Bernard et al. 1998; Owens et al. 1997; Wallbrink and Croke 2002) (Fig. 2). Conservative tracers that are stable and not altered by the sediment transport process, such as Caesium-137 (^{137}Cs), together with other natural tracers such as major elements (Olley and Caitcheon 2000) and mineral magnetism (Walling and Woodward 1995), are

Fig. 3. Sediment redistribution and storage on a large (300 m^2) experimental plot on a disturbed forested area including a skid trail, cross bank (water bar), and the adjacent general harvesting area (after Croke et al. 1999*b*). The "Red Granite" soil is well aggregated and not susceptible to dispersion. It is readily eroded from the skid trail but is readily trapped in the adjacent areas of lower disturbance. The "Metasediment soil" has a high stone and gravel content and has a comparatively low erosion rate on the skid trails. However, the slightly dispersive nature of the soil results in a higher sediment delivery across the general harvest area.



extremely useful in tracing the source and pathway of sediment within disturbed catchments. Sediment tracer techniques, including the use of ^{137}Cs inventories, possess a major advantage over the catchment monitoring approach since it overcomes the need to estimate the sediment delivery ratio applicable to a monitored sediment source (Peart and Walling 1986).

Our understanding of the nature of on-site erosion processes and their spatial variability has also been advanced through larger plot-scale experimental studies (e.g., Croke et al. 1999*b*; Luce and Black 1999). Many of these experiments were specifically designed to quantify the processes of sediment storage and redistribution and produce a more accurate assessment of hillslope sediment contributions and delivery rates than that previously possible from small-scale plot experiments (Fig. 3). Detailed experimental studies have also been undertaken on the spatial variability of important controlling variables such as saturated hydraulic conductivity (Woolhiser et al. 1996; Bromley et al. 1997; Ziegler and Giambelluca 1997*a*; Croke et al. 1999*a*). More detailed process understanding of the nature and rate of runoff generating mechanisms on these surfaces, and their spatial extent, will improve our ability to accurately predict the importance of these surfaces as dominant sediment sources (Dunne et al. 1991).

In reviewing the literature, it is apparent that to accurately predict the potential impacts of accelerated surface runoff and erosion processes due to harvesting and land clearing on stream water quality we require some understanding of three key components. These may be summarized as

- identifying the major sources of runoff and sediment and their spatial distribution with respect to streams
- describing the delivery pathway of each of these sources and its affect on sediment fluxes as runoff moves through the landscape from source to stream
- the effectiveness of best management practices with respect to sediment production and delivery

In the following sections we will provide a template for the consideration of these components. The application of this framework to a specific environment will require knowledge of soil characteristics, climate, topography, and local forest management practices.

The sediment delivery components

It is generally accepted that our understanding of the sediment delivery process and its components is limited. Novotny and Chesters (1989) suggest that the most feasible approach is to break down the process into three major components of overland flow, vegetative filtering, and channel processes, and develop quantitative models and descriptions for each component.

To assess and design the impact of surface erosion processes and land surface disturbance upon sediment delivered to the stream we introduce a simplified version of Novotny and Chesters' (1989) approach for which the two components are (1) runoff source strength (RSS) and (2) the nature of the delivery pathway (Fig. 4). The RSS represents the ability of a particular land surface to generate overland flow and the probability of this runoff reaching the stream network. This is a function of rainfall intensity, the degree and the size of the area of disturbance. In Fig. 4, the right-hand side of the diagram depicts situations where relatively large contributing areas led to the generation of much runoff and sediment. The net impact on stream water quality of this source strength is then moderated by the degree of connectivity to the stream.

We broadly classify delivery pathways as (*a*) new channels or gullies that are represented in the landscape as a definable channel that acts to concentrate overland flow and (*b*) diffuse overland flow pathways that are typically wide and shallow. The upper part of Fig. 4 shows cases where diffuse pathways predominate. The surface runoff that is generated on areas of high disturbance are slowed and reduced in volume as water moves through an area of low disturbance and vegetation downslope. In the lower part of Fig. 4, overland flow is concentrated in a channel or gully that formed as the result of scour below a road drainage outlet feature. These pathways are characterized by high-energy flow with little, or no, potential for the deposition of sediment. In this case the buffering of the source areas from the stream by the presence of vegetated areas adjacent to the stream is minimal. The channels or gullies effectively bypass the importance of vegetative filtering in reducing runoff and sediment fluxes.

The likelihood of runoff and hence sediment reaching the stream is expressed here as the degree of "connectivity". This term is used to describe the linkage or connection between a runoff source, such as a road or track outlet, and the receiving waters. There are a variety of degrees of connectivity that express whether a pathway is fully or partially linked to the stream (Fig. 5).

The combination of runoff source strength, RSS, and connectivity allow for some consideration of sediment delivery at the hillslope scale, i.e., from runoff or sediment source to the stream edge. Consideration of in-channel sediment transfer, storage, and routing processes is necessary to determine a whole-catchment response. Data on rates of sediment storage, transfer, and remobilization in channel systems is scarce and rarely considered in any catchment evaluation process. We necessarily place considerable emphasis on sediment delivery at the hillslope scale. It is at this scale that management practices can be most effectively manipulated to control sediment delivery to streams.

Runoff source strength

Identification of specific areas that actively contribute sediment to the stream channel network is a necessary prerequisite for understanding the sediment delivery process and developing successful sediment management programs (Roehl 1962; Dietrich and Dunne 1978; Khanbilardi and Rogowski 1984; Richards 1993). Traditionally, most attention has been given to the erodibility of a particular land surface. Intuitively, sediment delivery is more a function of the strength of the transport agent, be that surface overland, subsurface flow that returns to the surface, or direct channel flow, or a combination thereof. Large amounts of sediment can not be moved off-site without a sufficient discharge to transport this material. Recognition of the importance of runoff generating mechanisms in this process is paramount to the successful design of effective management strategies.

Runoff generating mechanisms in undisturbed forests, with few exceptions (Elsenbeer and Lack 1996), are dominated by subsurface storm flow (SSSF) through macropores and topographically con-

Fig. 4. Conceptual framework of how runoff source strength and the connectivity of the delivery pathway combines to determine the delivery of sediment to the stream network. The overall delivery of sediment to the stream varies from very little in the top left of the diagram to very high in the bottom right.

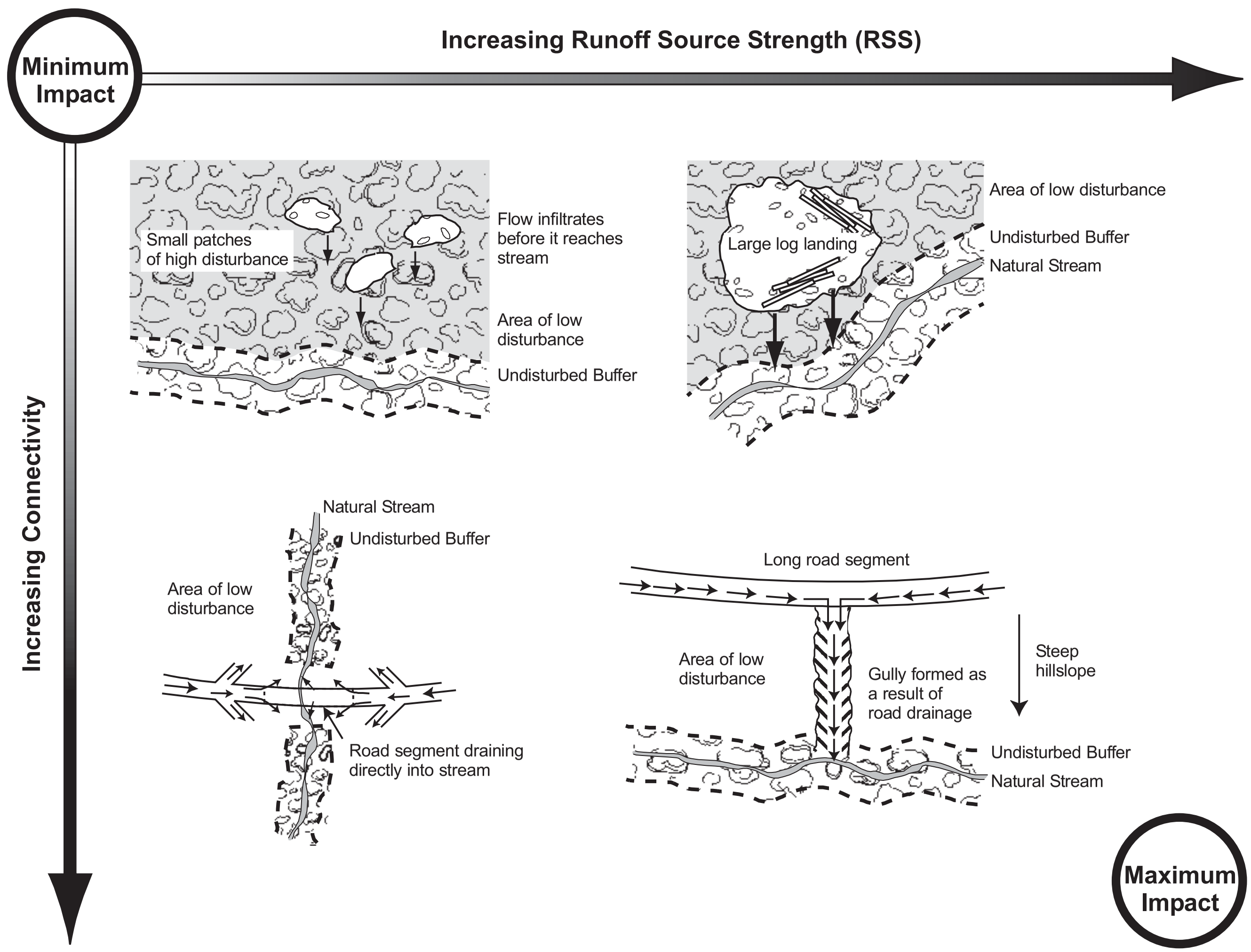
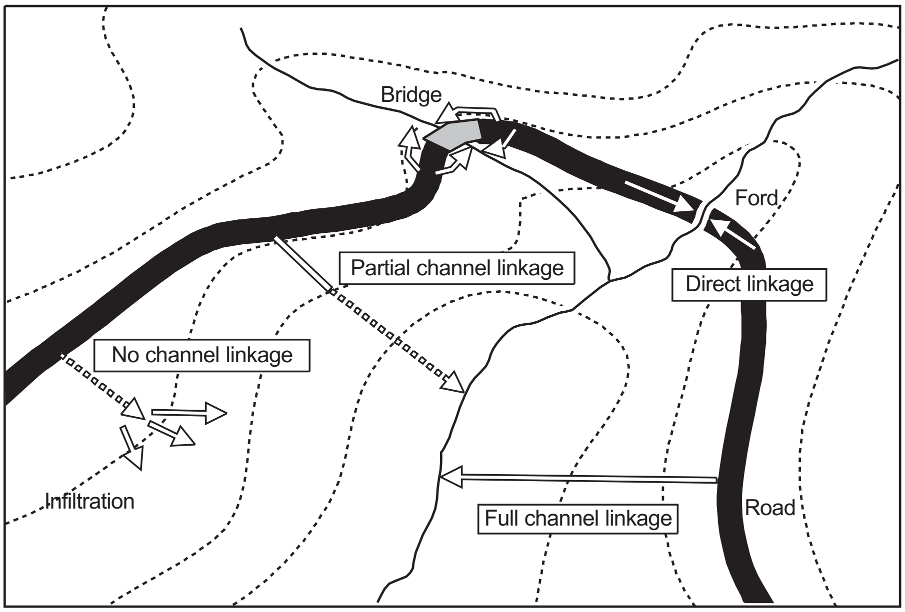


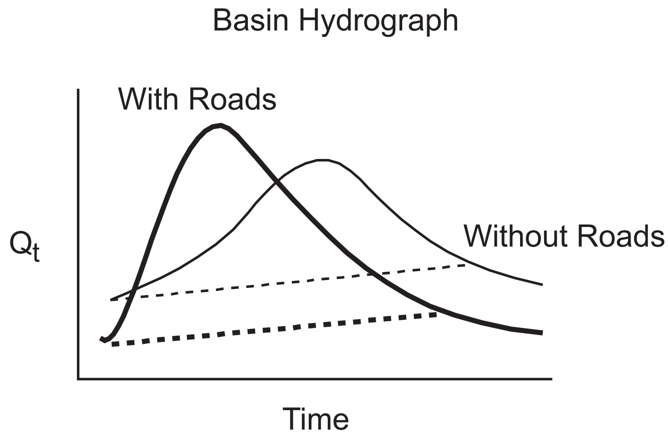
Fig. 5. The range of potential connectivity categories for a road. The fully connected segments are drained by a gully that has become part of the stream network; the partially connected segments are drained by a gully that stops prior to joining the stream network, direct connectivity as occurs at a bridge or ford where there is no hillslope between the road and the stream network. Where no gully or channel exists below a road drainage feature then the overland flow may be partly or fully dispersed, thus limiting or eliminating the connectivity.



trolled mechanisms such as saturation-excess overland flow (SOF) (Dunne and Black 1970; Moore et al. 1993; Bonell 1993). Infiltration-excess or Hortonian overland flow (Horton 1933) is rare in undisturbed temperate forests due to high infiltration capacities (Whipkey 1965; Freeze 1975; Bonell and Gilmour 1978; Talsma and Hallam 1980; Thomas and Beasley 1986). The relative impact of SSSF and SOF on water quality in pristine forests is regarded as minimal (Thomas and Beasley 1986). In logged forests, these runoff generation and delivery mechanisms are altered to varying degrees due to harvesting operations and especially road construction. Increased areas of compacted soil and altered ground cover have been shown to affect hillslope hydrological processes and catchment stream flows to varying degrees (Harr et al. 1975; Ziemer 1981; Megahan 1983; King and Tennyson 1984; Wright 1990; Malmer and Grip 1993; Jones and Grant 1996; Ziegler and Giambelluca 1997*a*, 1997*b*; Douglas et al. 1995). Jones and Grant (1996) claim, for example, that streamflow changes related to forest roads could be more important than those related directly to vegetation removal, although the separation of effects is extremely difficult to quantify in large basins. La Marche and Lettenmaier (2001) used a distributed hydrological-soil-vegetation model (DHSVM) (Wigmosta et al. 1994) to estimate the effects of forest roads on peak flows in nine basins in the United States. They concluded that the location of clear-cuts as they relate to road connectivity is more important than the total amount of clear-cuts in determining road effects on peak flows.

Disturbed land surfaces include unsealed roads, log haulage tracks, general harvesting areas and to a lesser extent, stream-side vegetated areas or riparian buffers. The following sections review the way in which surface runoff generation on these surfaces may impact upon sediment delivery processes and rates. The probability of this runoff reaching the stream will reflect both the volume of water generated

Fig. 6. Conceptual diagram outlining the dominant impacts of road runoff on the stream hydrograph (From Wemple et al. 1996). Note the higher and earlier peak discharges expected for catchments with roads.



and the distance to the stream network. This latter factor is rarely reported in any quantitative sense in the literature. It is important, however, to include this factor in any assessment of sediment delivery efficiency.

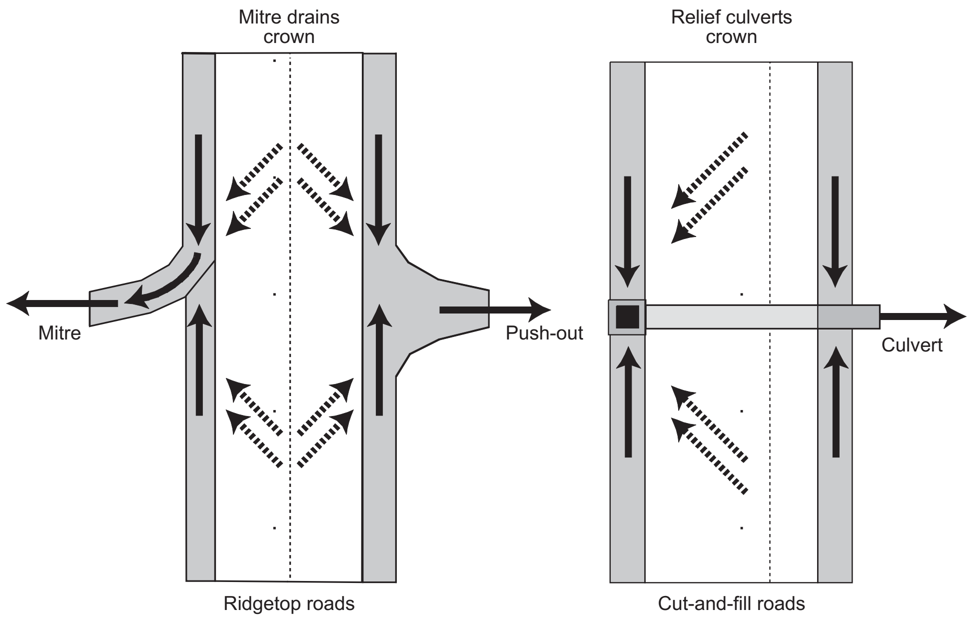
Road and track networks

Unsealed road surfaces and logging tracks can be regarded as one of the most hydrologically active areas within a logged forest for the majority of low to moderate rainfall events (Bruijnzeel and Critchley 1994; Ziegler and Giambelluca 1997*a*, 1997*b*; La Marche and Lettenmaier 2001) and thus are a major influence on runoff source strength. This is due largely to their compacted nature and low infiltration capacity (Luce and Cundy 1994; Flerchinger and Watts 1987; Ziegler and Giambelluca 1997*a*; Croke et al. 1999*a*; Luce and Black 1999; Ziegler et al. 2000). Reported estimates of infiltration rate on unsealed road and track surfaces range from 0.5 mm h^{-1} to 20 mm h^{-1} (Luce and Cundy 1994). Surface overland flow development is rapid and spatially uniform across the entire road network (Dunne and Dietrich 1982; Reid and Dunne 1984; Rijsdijk and Bruijnzeel 1991; Van der Plas and Bruijnzeel 1993; Luce and Cundy 1994; Ziegler and Giambelluca 1997*a*, 1997*b*; Luce and Black 1999).

Ziegler and Giambelluca (1997*a*) and Ziegler et al. (2004) identify four distinct features of unsealed roads that impact upon runoff generation and storm flow response. These include (1) highly compacted road surfaces and road side margins that produce overland flow and allow all surface water to run off rapidly; (2) cutbanks that intercept subsurface flow, then re-route it via the faster overland flow mechanism toward the stream channel; (3) ditches and culverts that capture both surface and subsurface flow and channel it more rapidly to streams; and (4) gullies developed at drainage outlets similarly act to channel surface and subsurface flow and deliver it more efficiently to streams. Factors (1) to (3) all contribute to the runoff source strength. The net effect of road runoff on the basin hydrograph is described in a conceptual model developed by Wemple et al. (1996) as shown in Fig. 6. The addition of roads to a forested landscape result in the changes to the rates of hydrologic processes as described above, resulting in higher peak discharge rates that occur earlier, than for the same environment without roads.

The relative contribution of surface and subsurface flow may be expected to vary with such factors as road type, soil depth, structure, and rainfall intensity (Wemple and Jones 2003). A dominance of roads that are cut into the hillslope, as opposed to roads that are aligned along the ridge-top (Fig. 7), may affect the relative contributions of these runoff sources (Megahan 1972; Wemple et al. 1996; Bowling and Lettenmaier 1997; La Marche and Lettenmaier 2001). La Marche and Lettenmaier (2001) suggest, for

Fig. 7. Typical road drains used on ridge-top and cut-and-fill roads. Mitre drains are extensions of the road side ditch used to divert runoff onto the adjacent hillslope along ridge top roads. Drainage on cut-and-fill roads is typically provided by a relief culvert that redirects runoff onto the fill-side of the road and then onto the vegetated area. Push-outs are often used in road saddles or topographic lows and bring runoff from two segments of road draining to a central point.



example, that interception of subsurface flow and its routing to the channel network can result in lowering of the below-road water tables. Some experiments indicate that for small, commonly occurring storms, road-related surfaces contribute more to total excess rainfall than all other land surfaces combined (e.g., Ziegler and Giambelluca 1997*a*). For high intensity or long duration storm events, when excess-rainfall is generated from non-road areas, the contribution of other land surfaces can dominate because of their larger aerial extent (Ziegler and Giambelluca 1997*a*).

General harvesting areas or disturbed hillslopes

General harvesting areas (GHA) or logged hillslopes typically represent the largest land surface by area within a forested catchment. Forest harvesting practices in most countries now operate a system of integrated or selective logging whereby trees are removed from selected compartments on a rotational basis. Inter-harvesting cycles of 40–50 years are common for native hardwood forests and shorter cycles are often used in softwood plantations. Runoff generation on these surfaces typically develops slowly, predominantly on the bare or more disturbed parts of the hillslope. Croke et al. (1999*a*) describe runoff generation on general harvesting areas of varying time since logging and report slow time to runoff responses even under extreme rainfall intensities of 110 mm h^{-1}. The rainfall simulator experiments, and a detailed analysis of saturated hydraulic conductivity (*K*s) values within a 300 m^2 plot area, confirmed the patchy nature of runoff generation and the high degree of spatial variability of infiltration properties on these surfaces (Fig. 8). The wide spread of *K*s values confirms the existence of some areas of compacted soil with low hydraulic conductivities, and adjacent areas of high conductivity representative of undisturbed or less disturbed forest soils. This study also demonstrated some degree of recovery in soil hydraulic properties with time since logging (Fig. 9).

Although partially disturbed during harvesting, the retention of a high degree of forest vegetation also contributes to the lack of sediment transport in these areas. Channelised flow is rarely generated within

Fig. 8. Comparison of saturated hydraulic conductivities (*K*s) from a skid trail (snig track) and adjacent general harvesting area within a sandy granite soil in southeastern NSW Australia. The much wider, flat curve of the GHA with a larger range of *K*s values (standard deviation) indicates the presence of disturbed areas with low *K*s and less-disturbed areas with higher values.

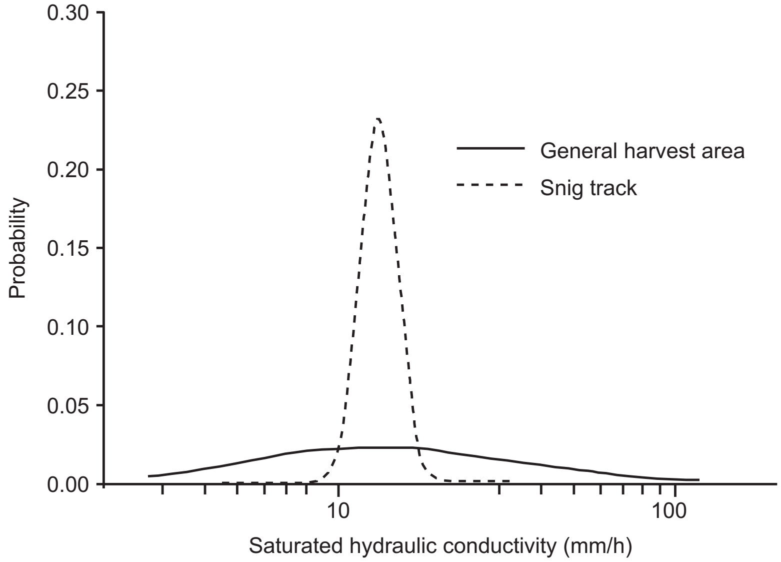
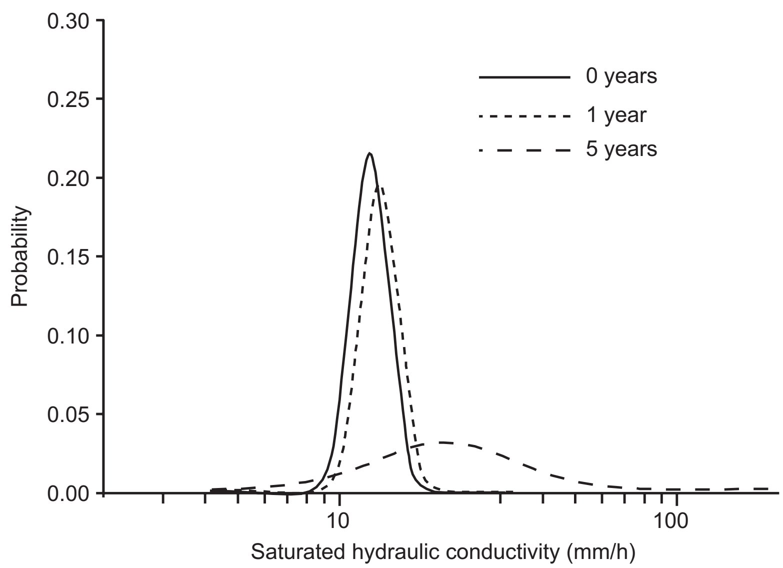


Fig. 9. Changes in *K*s of a skid trail (snig track) on three sites of varying age since logging; 0, 1, and 5 years after logging. The curves indicate some recovery in permeability of a sites surface soil over time.



the GHA, limiting the ability of runoff to transport large amounts of sediment. Sediment generation is also restricted by the availability of loose material on the surface, often dominated by organic material (Prosser and Williams 1998; Croke et al. 1999*a*; Ziegler et al. 2000).

Riparian buffer strips or streamside vegetation areas

Forest management practices in many regions leave an undisturbed vegetated buffer strip immediately adjacent to the majority of streams and drainage lines. This buffer strip or riparian zone has a range of functions including maintaining the stability of the stream channel, providing riparian habitat, and a long-term recruitment of woody debris, regulating light and water temperature in the stream and acting as a vegetative filter for runoff between the areas of disturbance and the stream network. This final function may be considered as the last line of filtering as sediment generated on roads, tracks, and other compacted areas frequently pass through the general harvest areas prior to entering the buffer strip. Characteristics of these pathways are considered in the next section.

It is widely recognized that disturbance of the riparian zone inhibits the functions described above. Furthermore the proximity of the riparian zone to the stream minimizes the likelihood of the managing sediment delivery as described in the following sections.

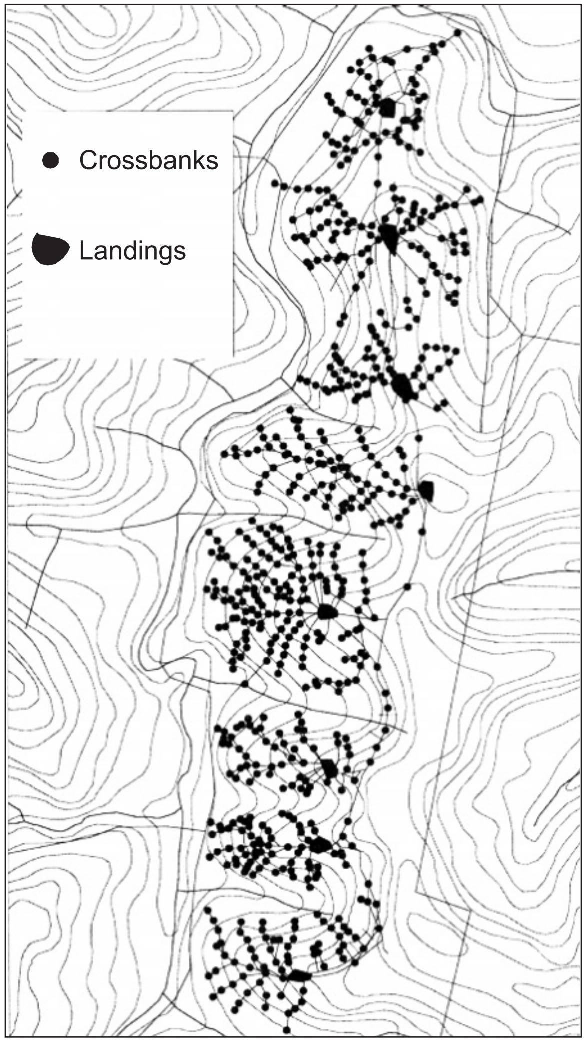
Hydrologically, riparian zones are recognised worldwide as having a key role in moderating the impact of land use on stream water quantity and quality (Norris 1993). Riparian zones are normally characterized by a very rough soil surface, often with an intact litter layer. The soil is porous with many macropores and the rooting zone is frequently deep. Sediment deposition, which occurs as a result of reduced runoff due to increased infiltration, relies on there being an unsaturated surface in the riparian zone. The very porous nature of the undisturbed riparian zone soil assists in this process, whereas, the presence of a wet zone or capillary fringe from a water table inhibits it. In some circumstances the riparian zone can remain moist throughout the year due to the influence of the water table and associated capillary fringe from an adjacent stream (Abdul and Gillham 1989). Herron and Hairsine (1998) provide a model for the prediction of this effect in a range of environments with a simple consideration of climatic, topographic, soil, and antecedent inputs. Where only small flows of overland flow enter the riparian zone it is possible that all the overland flow will infiltrate in the riparian zone so that the hillslope is disconnected from the stream (Hairsine et al. 2002).

Characteristics of the delivery pathway

Each runoff–sediment source has its own very specific delivery pattern dependent upon its spatial distribution within the catchment and the management practices employed. Forest roads for example have a delivery pattern largely determined by the arrangement and location of drainage structures such as culverts and mitre drains within the catchment. If no drainage structures exist, sediment delivery will be strongly influenced by topography at the road and hillslope. In contrast, drainage of temporary roads or forest snig tracks typically results in a more dispersive pattern (Sidle et al. 2004). Here runoff and sediment is often redistributed parallel to the contour, in some cases via a network of cross drains. Figure 10 shows a dense network of snig tracks and the cross drains that successfully disperse overland flow.

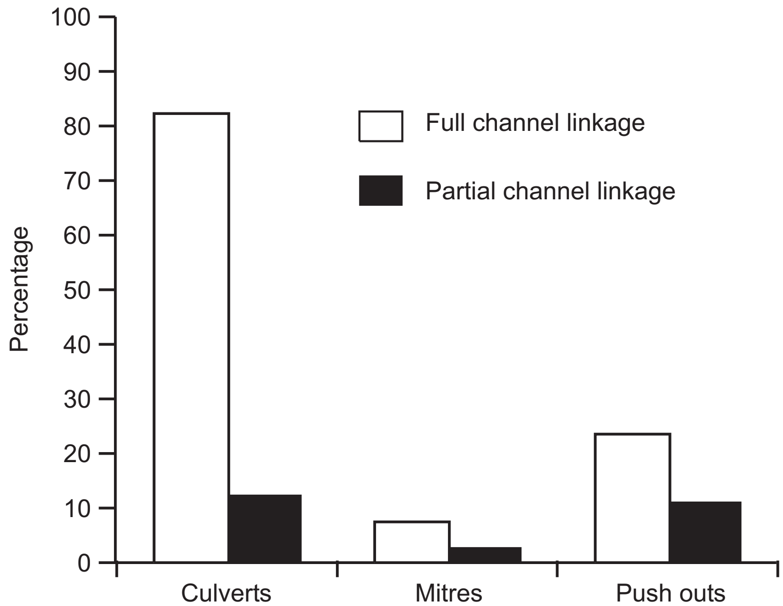
A number of studies have demonstrated the significance of concentrated flow paths at road outlets with respect to channel initiation and gully development (Montgomery 1994; Wemple et al. 1996; Croke and Mockler 2001; La Marche and Lettenmaier 2001). Montgomery (1994) noted that concentration of road runoff has various geomorphic effects including the initiation or enlargement of a channel and slope instability below the drainage outfall. Montgomery (1994) found a positive correlation between gully development and road contributing area and adjacent slope. Data were used to develop simple empirical relationships to determine critical thresholds to limit gully development. Gully initiation at road drain outlets has also been recorded in a forested catchment in the southeastern part of NSW, Australia, resulting in a 6% increase in the natural drainage density of the catchment over a period of approximately 30 years (Croke and Mockler 2001). The study also recognised a clear relationship between gully initiation and the type of drainage structure used (e.g., mitre drain or culvert) with most gullying associated with culvert pipes on steep hillsides (Fig. 11). Gullied pathways in this study were also differentiated using an area–slope threshold, similar to the general form identified by Montgomery

Fig. 10. Example of cross bank locations draining a forest compartment with snig tracks or skid trails in southeastern NSW Australia. These cross banks are designed to disperse runoff from skid trail segments onto the adjacent GHA without concentrating runoff (from Hairsine et al. 2002).



(1994) in the United States, providing some confidence that empirical area–slope relationships may prove to be a valuable management tool in limiting gully initiation at road drainage outlets. La Marche and Lettenmaier (2001), however, used a multiple regression model to explain the occurrence of gullying in the Deschutes River Basin in the United States and found that neither slope nor road or culvert drainage areas were statistically significant. This study found only hillslope curvature and downslope distance to the natural stream channel to be statistically significant. The authors suggest that the non-significance of culvert drainage area may relate to the absence of road slope in the analysis and the observation that runoff frequently infiltrates in ditches with low gradients, thus limiting the overall contribution of surface and subsurface runoff to the culvert outlet. Furthermore the authors tested the empirical relationship in two additional catchments and found that the statistical relationship accurately predicted the occurrence and non-occurrence of gullies for 81% of the sampled drainage outlets. In contrast, in

Fig. 11. Variations in percentage of road outlets fully and partially connected or linked to the stream network via a channel or gully according to major drain type (after Croke and Mockler 2001).

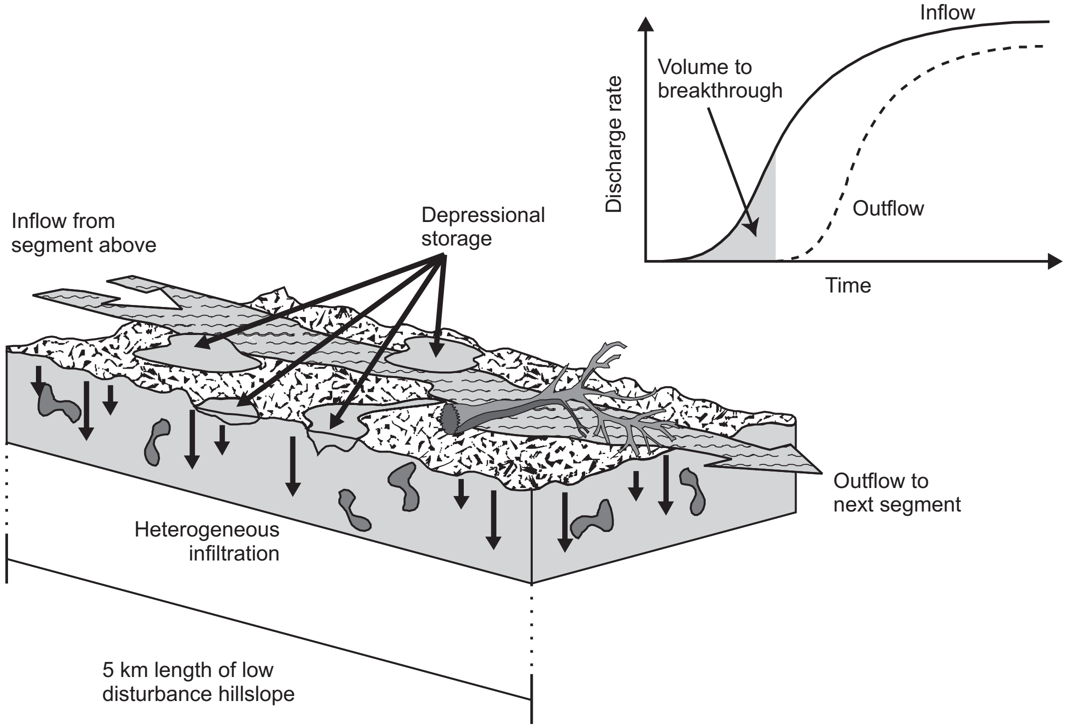


the Mae Taeng catchment in northern Thailand, road length was found to be the single most important variable leading to increased runoff and sediment yield (Douglas 1999). This highlights the importance of replicating these sort of studies in as wide a range of forest-road environments as possible. There is little doubt that simple empirical relationships such as those developed by both Montgomery (1994), Wemple (1994), Croke and Mockler (2001), and La Marche and Lettenmaier (2001) play a key role in management strategies to control the delivery of road-related runoff to the natural stream network.

Diffuse overland flow paths have received less attention than the more obvious morphological pathways associated with channel or gully development. This is partly related to the difficulty of quantifying attributes of the shallow overland flow during storm events and appropriate techniques to quantify pathway width, depth, velocity relationships as surface runoff moves through the dense litter, soil, and vegetation layers. Diffuse pathways, which are characterized by non-concentrated shallow, wide runoff plumes, have been observed at the outlets of road drainage structures but descriptions of the fate of these pathways are rare. Croke et al. (1999*a*) describe the nature of overland flow pathways as runoff that is redistributed at water bars draining forest skid trails in south-eastern Australia. Plumes were on average less than 2 m wide and dispersed rapidly amongst the litter layer once the concentrated runoff was discharged onto the adjacent hillslope. Using fluorescence dye, the travel distance and velocities of the pathways were estimated and in the majority of experiments the overland flow plumes had infiltrated into the soil within 25 m of the outlets, even during extreme rainfall intensities of 110 mm h^{-1} (Croke et al. 1999*a*).

Hairsine et al. (2002) proposed an approximate way of describing the movement of diffuse overland flow pathways across the land surface from concentrated outlets such as a road drainage structure. This approach assumes that segments of the pathway have a finite capacity to infiltrate water, which is filled before the plume moves on to the next segment (Fig. 12). In this way the movement of the plume to the stream edge is controlled by the ratio of the volume of water leaving the runoff generation area and the length of the diffuse pathway to the stream. The proposed model uses a statistical description of the storage capacity of each pathway segment, so that predictions of the length and likelihood of the plume reaching the stream are probabilistic.

Fig. 12. Schematic of the major components of the overland flow plume model (from Hairsine et al. 2002). The volume of water flowing across the hillslope segment is reduced by infiltration and filling of the depressional storage. If these losses exceed the total inflow onto the hillslope then the source is disconnected from the stream.



Source to stream connectivity

The concept of connectivity relates to the degree that a runoff source is linked to the stream network. Both of the diffuse and concentrated flow pathways may be connected to the stream network to varying degrees. These are best described using the framework and terminology of Wemple et al. (1996), as later used by Croke and Mockler (2001) and La Marche and Lettenmaier (2001), to describe the nature of road-to-stream connectivity.

The connectivity of the road drainage to the stream network determines the efficiency by which runoff intercepted by road cutslopes and road surfaces is routed to the stream via drainage outlets (La Marche and Lettenmaier 2001). Road runoff may (*a*) infiltrate into the soil directly, (*b*) enter the stream directly at a stream crossing culvert, (*c*) infiltrate below a gully that does not extend to the stream channel, and (*d*) enter a stream channel indirectly through the formation of a gully below a relief culvert. In case (*a*) or (*c*) the road drainage is not connected to the stream network. In cases (*b*) and (*d*), the road network is connected to the drainage network either directly or indirectly (Fig. 5).

Where overland flow pathways are diffuse, the degree of connectivity depends on the relative runoff source strength and the available length of hillslope where infiltration can occur (Fig. 4). Where only a small buffer and (or) area of low disturbance is present below a runoff source the sediment load is reduced through settling and adhesion of sediment to vegetation as runoff moves across the landscape. Where the pathway is far below the runoff source there is more opportunity to reduce the volume of overland flow and in some cases disconnect the runoff source from the stream. This is particularly useful in reducing the amount of fine suspended sediment reaching the stream.

A simple design approach to minimizing source to stream connection

The spacing of road drainage features is a key design variable for the effective management of sediment delivery from roads and tracks. A further design variable is the position of the drainage outfall point in the landscape. For example, a culvert discharging into a stream head or first order ephemeral stream will greatly increase the impact of road runoff and sediment on the stream. In contrast, a culvert that directs road runoff onto a large divergent slope will reduce the volume of both overland flow and associated sediment, thereby reducing sediment delivery to the stream.

There are three key processes to consider in the design of the spacing and location of road drainage features for surface erosion control and water quality protection:

- erosion of the road and the parallel drain (sediment generation on the road and in the road drain)
- gully incision on the hillslope immediately below the road drainage outfall
- the infiltration of the non-channelized runoff on the hillslope below the road drainage outfall

The proposed design approach described below uses three steps to sequentially address each of these processes. This approach results in a drainage design for the road that considers properties of both the road and the landscape in which it is constructed.

Step 1: Minimizing runoff from and erosion of the road and road drain

Minimizing erosion of the road or track surface has historically been a major design objective of forest planners and engineers (Lynch et al. 1985). Minimizing erosion of the road surface and ditch drain is important in providing a stable surface that requires low maintenance whilst at the same time limits the delivery of sediment to the outfall hillslope. The major design objective is to manage the rate of runoff that occurs on the road surface and in the adjacent road drain. It is the runoff rate at the outlet of the drainage structure during major rainfall events that provides the driving influence for sediment erosion and transport.

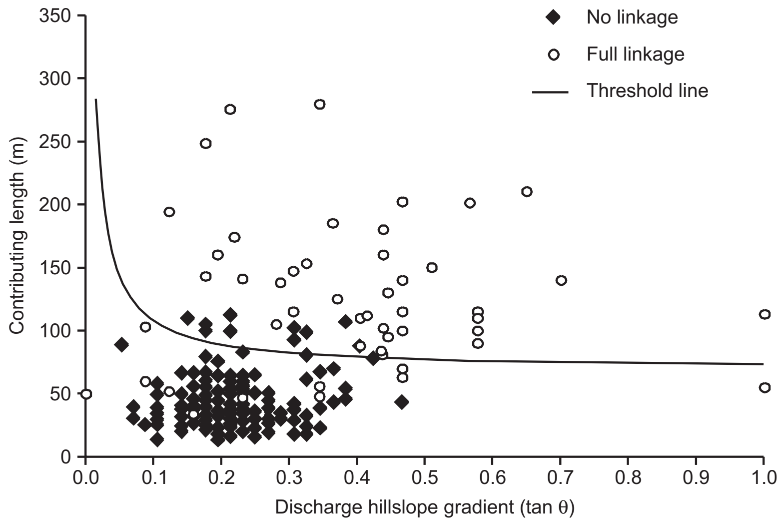
The slope of the road or track in the direction of vehicular travel and rainfall intensity are the two important design factors in the first design objective. The stream power of the flow in the road drain is proportional to the product of the discharge and the road surface slope. Normally, flow will increase linearly with distance downslope so, for a given slope, stream power also increases linearly with distance downslope and rainfall intensity. Observations of drain scour suggest that there is normally a threshold stream power above which the drain scours so that it becomes a source of sediment. Minimizing the sediment delivery to the road outfall demands that drain scour be avoided. This is achieved by selection of appropriate road drainage spacing. In practice, tables of drain spacing for a range of road slopes have been developed regionally using only this design step. These tables are based on observations of scour of roads in that region and are only adequate if design steps two and three do not limit the selection of road drainage spacing.

Step 2: Preventing gully formation at the drainage outlet

As runoff leaves a drainage structure and is discharged onto the adjacent hillslope there is potential for incision that can lead to gully formation as described in the sections above (Montgomery 1994; Wemple et al. 1996; Croke and Mockler 2001). The overall form of the threshold relationship in these case studies is similar and indicates the existence of some critical value of contributing road length or area above which gully initiation appears likely to occur. Croke and Mockler (2001) suggest that the threshold function for a catchment in south eastern NSW is represented by

$$L_{\mathrm{ct}} = \frac{25}{\sin\theta} \qquad [1]$$

Fig. 13. The threshold curve used to separate gullied and non-gullied pathways at road outlets in a forested catchment in southeastern Australia (from Croke and Mockler 2001). The curve is used to determine the contributing road lengths and discharge hillslope gradients above which gully development is likely to occur.



where L_{ct} is the length of road segment (metres) to initiate gullies at the outlet and θ is the slope angle of the discharge hillslope in degrees (Fig. 13). This relationship can be used in the design mode by adjusting the road segment length (the distance between drainage features) so that it is always below L_{ct}. Contributions of runoff from cutslope interception on cut-and-fill roads have also been identified (Montgomery 1994; Wemple et al. 1996; Croke et al. 2001). The above relationship can also be expressed in terms of the critical area of hillslope and cutslope generating excess runoff (both surface and subsurface) that is intercepted by the road and contributes to gully formation at road outlets on cut-and-fill roads. This term is more difficult to determine from field measurements or digital elevation models than the measure of road length.

Step 3: Minimizing delivery of non-channelized overland flow to the stream

If the runoff leaving the road drainage structure does not incise the outfall hillslope there is opportunity to reduce the sediment load on the hillslope and hence arriving at the stream edge. In forestry environments the outfall hillslope is normally rough and often fully covered with vegetation and surface litter, making the surface hydraulically rough. This dissipates the stream power and reduces the possibility of gullying. The rough vegetative surface reduces the velocity of the flow and its ability to carry coarse sediment downslope (Croke et al. 1999*b*). However, fine sediment (approximately less than 63 μm) is more difficult to manage, as the reductions in velocity associated with the entry of the flow onto the hillslope are insufficient to induce deposition of this sediment (Barling and Moore 1994). However, by infiltrating a portion of the overland flow, which is delivered to the outfall hillslope, the fine sediment it carries is trapped in the soil and litter thereby reducing delivery to the stream. Hairsine et al. (2002) provide a structured approach to the design of this process that uses the length of the road segment and the available discharge hillslope length as its major inputs. The model predicts the length of the overland flow plumes and the volume of water delivered to streams and presents these probabilistically for a range of rainfall-event scenarios. For example, the user may choose the design criteria that runoff will not reach the stream in 95% of cases for a rainfall event of specified duration and recurrence interval. To apply this methodology in a new region requires inputs of road runoff coefficients, design rainfall intensities, and infiltration properties of the outfall hillslope. Design rainfall intensities are normally available from local flood design texts. Knowledge of the infiltration properties of the outfall hillslope will need to be measured or assumed.

Effectiveness of best management practices in controlling sediment delivery

Controlling the runoff source strength and delivery of sediment and attached nutrients is an important process in minimizing off-site impacts of forestry operations. Several best management practices are used in forestry operations to mitigate the potential impacts of logging on stream ecology and water quality. Some of the more universally applied practices include the use of riparian buffer strips, patch harvesting, siting and design of roads and road crossings to minimize sediment inputs, and restrictions to logging activities in relation to slope and soil type. There is little doubt that the effective implementation and construction of these practices can significantly reduce sediment delivery to streams in managed forests. For example, Hornbeck and Reinhart (1964) examined the effects of on-site prescriptive measures (e.g., bars across skid trails, a ban on stream crossing, and the location of roads away from streams) on sediment concentration in the United States. Suspended solids concentration varied from 56 000 mg/L where no prescriptions were employed to 15 mg/L when all of the above were imposed. Lynch et al. (1975, 1985) also report that while BMPs did not completely prevent off-site impacts, the impacts were relatively small and of no direct concern to water quality standards. Grayson et al. (1993) also found that applying a strict enforcement of forest code prescriptions (e.g., suspension of logging during wet weather, protection of runoff producing areas with buffer strips, and the management of runoff from roads, skid trails, and log landings) eliminated intrusion of sediments and pollutants into streams.

Road and track drainage

As outlined in the previous sections, managing road runoff is a significant challenge with respect to controlling sediment delivery in managed forests. Considerable attention should be given to limiting sediment and runoff production from these areas. Numerous strategies have been developed to limit sediment production from forest roads and tracks, including revegetation, gravelling, and regular maintenance (Haupt 1959; Diseker and Richardson 1962; Kidd 1963; Dyrness 1970, 1975; Carr and Ballard 1980; Cook and King 1983; Burroughs et al. 1984; Kochenderfer and Aubertin 1987; Burroughs and King 1989; Heede and King 1990) and these have been found to be successful in limiting sediment delivery to streams. The discontinued use of skid trails and logging roads between cutting cycles is seen as a significant factor in limiting sediment supply for transport. The intensity of traffic usage is also seen as a key factor in the persistence of these areas as a sediment source (Reid and Dunne 1984; Luce and Black 1999). Luce and Black (1999) report the implications of road maintenance on the availability of this material using monitoring data on sediment production rates from entire road segments in Oregon, United States.

Croke et al. (2001) also report that redistributing runoff at water bars along tracks immediately after logging was a successful method in reducing the contribution of water and sediment to streams, particularly during small to medium rainfall events (2–10 years recurrence intervals). For a 100 year recurrence interval storm, both the hillslope and snig track were found to generate runoff. Under these conditions the ability of the hillslope to absorb excess runoff is reduced. The spacing of cross banks becomes critical under these conditions, where the length of the discharge plume must not exceed the designated cross-bank spacing so the plumes do not link. Design principles to guide the spacing of water bars and road drains are therefore crucial in limiting overland flow delivery to the stream.

The effectiveness of a combination of snig track drainage, the sediment trapping ability of the general harvest area, and a riparian buffer zone for a six-year post harvest period in southeast Australia was demonstrated in a recent study using radionuclide tracers (Wallbrink et al. 2002). Using an inventory of the sediment tracer caesium 137, this study found that the snig tracks and log landings were the major source of sediment moving within the compartment. Of the sediment eroded from these areas 18, 54, and 28% was trapped by the cross banks, general harvest area, and filter strip, respectively. The passage of overland flow from the highly disturbed areas though the cross-bank diversion, general harvest area, and buffer strip resulted in a minimal delivery of sediment to the stream.

Forest buffer strips

Streamside vegetated areas are an important management tool in the protection of water quality from surface erosion processes for two primary reasons. Firstly, increased hydraulic roughness within the buffer or filter strip, largely determined by the density of vegetation and roughness elements, acts to slow surface flow velocities and induce sediment deposition, thereby reducing total sediment loads delivered to the stream (Barling and Moore 1994). Secondly, high hydraulic conductivities within these vegetated areas promote increased surface water infiltration, limiting the delivery of overland flow and associated pollutants to streams.

Overall, the literature confirms that vegetated areas perform well in relation to these functions (Aubertin and Patric 1974; Tollner et al. 1976; Karr and Schlosser 1978; Martin and Pierce 1980; Clinnick 1985; Lynch et al. 1985; Borg et al. 1988; Norris 1993; Barling and Moore 1994; Pearce et al. 1998; Ward and Jackson 2004). Consensus on their ability to trap the very fine-grained silt and clay material under certain hydrological conditions is less conclusive. The ability of the buffer strip to reduce the volume of overland flow by infiltration processes is sensitive to the prevailing hydraulic properties of the area and to the moisture holding properties of the soil. Streamside filter strips may act as runoff sources due to rising groundwater levels in “wet areas” immediately adjacent to the stream (cf. O’Loughlin 1981). The trapping of very fine-grained material is likely to be highly dependent upon runoff infiltration mechanisms within the buffer strip.

The placement and width of buffer strips in catchments is a contentious issue. Buffer strips have several functions and the emphasis placed on each of these functions will depend on a wide range of environmental and organisational issues. Here we focus only on the role of the buffers in mitigating the inflow of sediment and associated pollutants from the upslope areas.

There are two possible approaches for locating buffer strips to serve this function; one based on determining appropriate sediment transport distances through the buffer strip and the other that attempts to protect runoff-generating areas in the landscape. In the case of the former, a 30 m buffer is typically regarded as effective in trapping most of the sediment from cleared areas, although absolute width is dependent upon specific site conditions (Clinnick 1985; Barling and Moore 1994). All the available literature on adequate buffer strip widths is, nonetheless, site-specific, and in many instances in steep terrain achieving a 30 m buffer strip width is impractical (Trimble and Sartz 1957; Packer 1967; van Groenewoud 1977; Corbett et al. 1978; Graynoth 1979; Bren and Turner 1980; Borg et al. 1988). There is little or no data that can be used to predict acceptable buffer widths under variable catchment characteristics (cf. Ziegler et al. 2004). Borg et al. (1988) found that halving the buffer strip widths from 200 m to 100 m and from 100 m to 50 m had little if any detrimental effect on water quality. Their complete removal, however, led to changes in the stream channel profile and to algal blooms. In a recent study, Davies and Neilson (1994) examined the impacts of forest logging on in-stream habitat, fish, and macro-invertebrate populations and related the observed impacts to the width of the riparian buffer strip at each site. Their conclusions state that “all impacts of logging were significant only at buffer widths of less than 30 m”. Herron and Hairsine (1998) also examined a scheme for evaluating the effectiveness of riparian zones in reducing overland flow to streams and suggested that a riparian zone width not exceeding 20% of the hillslope length is a practical management option. They also concluded that buffer zones need to be distributed around the stream network where upslope sediment sources exist, if riparian buffers of realistic widths are to be effective.

Table 1. Summary of sediment management measures in forest environments.

Management of runoff source strength	Management of sediment delivery path way
Unsealed roads	Unsealed roads
Drainage spacing	Drainage spacing
Road drains need to be constructed and maintained at spacings that minimize the sheet and rill erosion on the road	The spacing of road drains should also consider the design criteria of preventing gulling at the road drainage outfall and the minimization of the delivery of diffuse overland flow to the stream
Surfacing	Drainage position
Resurfacing of roads should attempt to minimize the availability of fresh fine sediment for subsequent erosion	Road drains should not discharge into or near drainage lines. They should discharge onto planar or diverging slopes
Position	Road position
Wherever possible roads should be positioned on ridge tops or near to ridge tops to prevent capture of runoff from the hillslope above	Roads should be positioned to maximize the length of the flow path of overland flow leaving the road
Traffic management including closure	Stream crossings
Where practical, forestry roads should be restricted or closed to traffic, which disturb the road surface thereby generating more available sediment	Stream crossings should be constructed to minimize or eliminate the area road draining directly into a stream
Harvest tracks and other compacted areas	Harvest tracks and other compacted areas
Banks	Location
Compacted tracks and landings should be segmented into small units by banks to disperse runoff water	Harvest tracks should be laid out from ridge top log landings
Location including landings	Banks
Log landings should be located on ridge tops to minimize the runoff capture from upslope	Post logging closure of tracks should ensure runoff is dispersed in adjacent harvest areas and buffers
General harvest area	General harvest area
Minimizing disturbance	Selective logging
Disturbance of the soil during logging operations should be minimized so that the majority of the soil surface remains protected by litter and vegetation cover	Selective logging should be used wherever possible to maximize the flow path length in low disturbance areas of runoff from the harvest area
Buffer zones	Buffer zones
Disturbance	Extent
Buffer zones should be subject to no or minimal disturbance during the logging operations	Buffer zones should protect all drainage lines including ephemeral drainage lines
Extent	Width
Buffer zones should extend to protect all drainage lines including ephemeral drainage lines	Buffers should be of adequate width so that they are able to filter inflowing overland flow (approximately 20 m either side of all drainage lines)

Summary

The principles and processes for managing sediment delivery in forestry environments have been reviewed. Best management practices that minimize the generation and the delivery of sediment to streams in such environments have also been described. We conclude by summarizing the actions required to ensure the minimization of sediment movement to streams within managed forests (Table 1). This table can be used as a checklist to examine existing practices and as a general guide to additional possibilities to manage the delivery of sediment and attached nutrients to streams.

Through the review of the many studies described in this paper an overall framework of sediment movement has emerged. Sediment is generated from a range of soil surfaces with roads and tracks being universally important. Part of this sediment is delivered to the stream with this proportion being determined by the characteristics of the pathway. Also major new sources of sediment can be generated where concentrated overland flow is sufficient to have incised new channels or gullies. For all of these sources a combined approach of reducing the source strength and enabling the delivery path to trap mobilized sediment, thereby reducing connectivity, is a sound approach to managing this problem. Table 1 sets out the principles of this combined approach using landscape components to structure the suggested management principles.

Conceptually separating runoff source strength and the delivery processes is useful in guiding the management of forested landscapes. This approach is adaptable to road, tracks, and other forms of soil compaction and related disturbance.

Three areas of follow-on investigation that have been identified during the course of this review:

(1) The automation of design approaches within geographic information systems. This will lead to forestry planning that adapts universal principles of sediment control to local conditions.

(2) The extended use of sediment tracer budgets to further refine the targeting of remediation measures. It is expected that this will ensure costly-control measures are well targeted across a range of environments.

(3) Design and evaluation of near zero-impacts forestry systems where no significant changes in sediment movement is expected compared with undisturbed forested catchments. This goal may be appropriate for catchments of especially high ecological value or in water supply catchments where the cost of water treatment will be reduced through such land management measures.

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